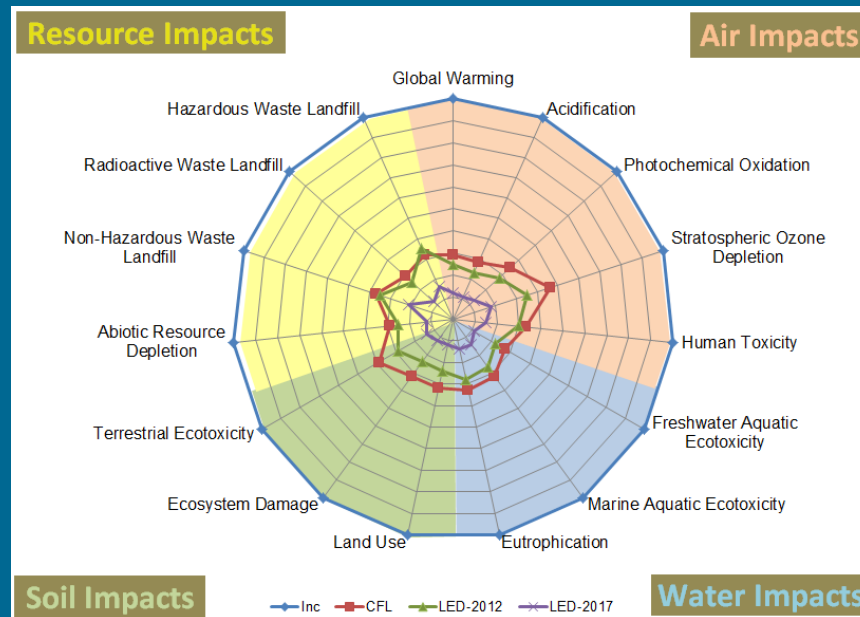


Life-Cycle Environmental Impact of LED Lighting



July 2012

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Pacific Northwest National Laboratory
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N14 Energy

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 - Brad Hollomon, Compa
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- Reviewers and Advisors
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- Review existing literature on energy and environment assessments of lighting options.
- Determine environmental performance over the lifecycle of lighting options.
- Determine end of life impacts of LED products.



- ▶ *Evaluate energy and environmental impacts of lighting options over the full life - including raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling.*

Energy

Manufacturing

Transport

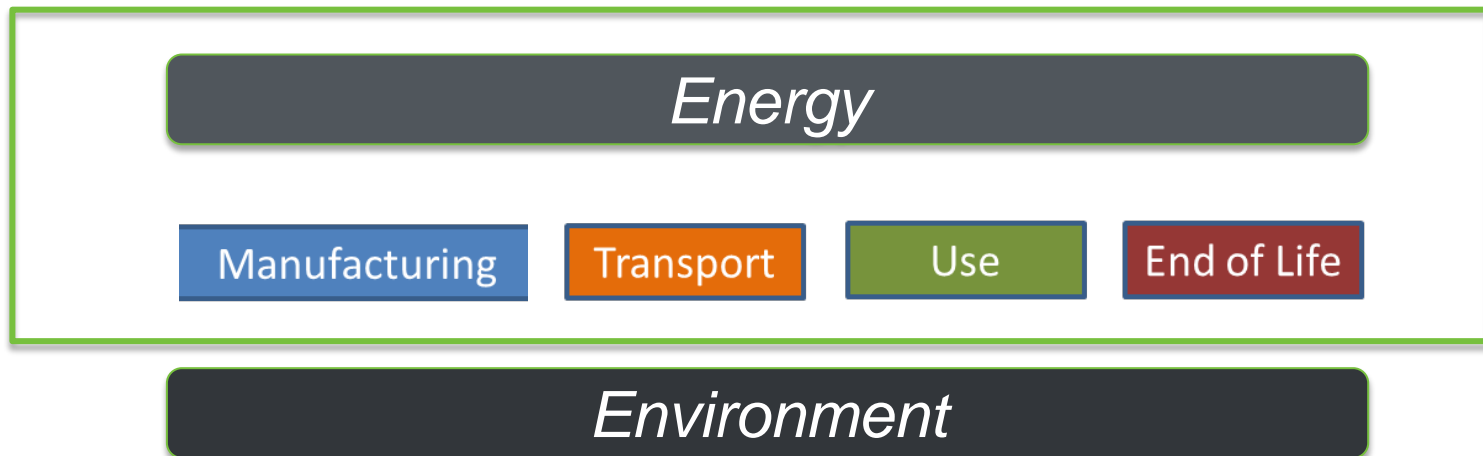
Use

End of Life

Environment

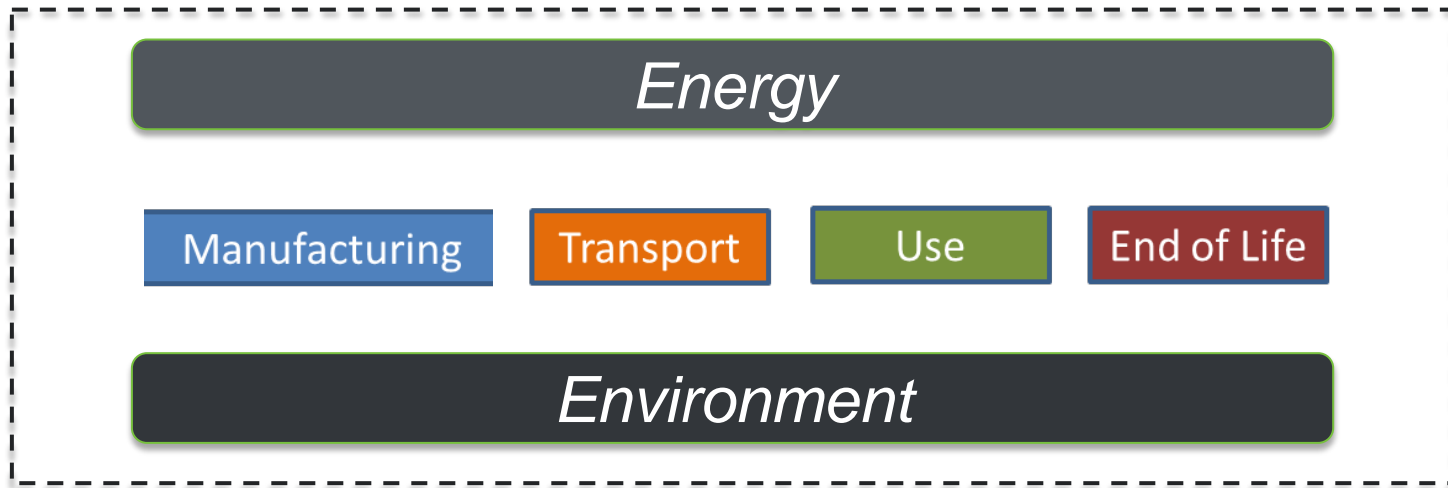
- ▶ *Part 1: Focus on energy and LCA evaluations performed by prior researchers.*

Part 1

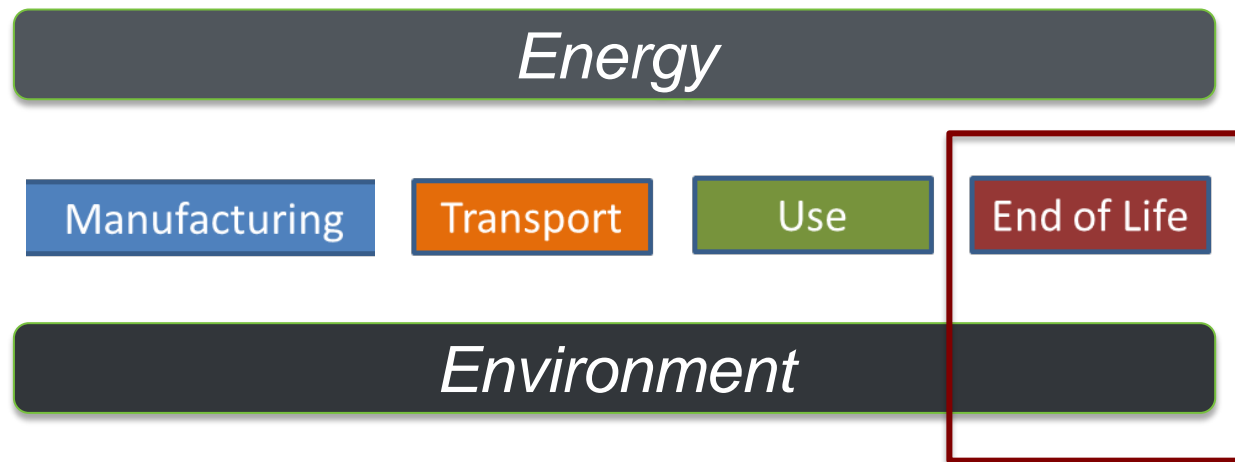


- ▶ *Part 2: Focus on energy and environment with manufacturing process not documented in prior reports.*

Part 2

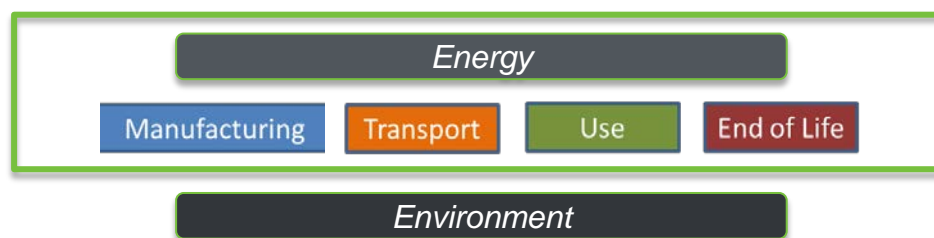


- ▶ *Part 3: Focus on end of life environment impact.*

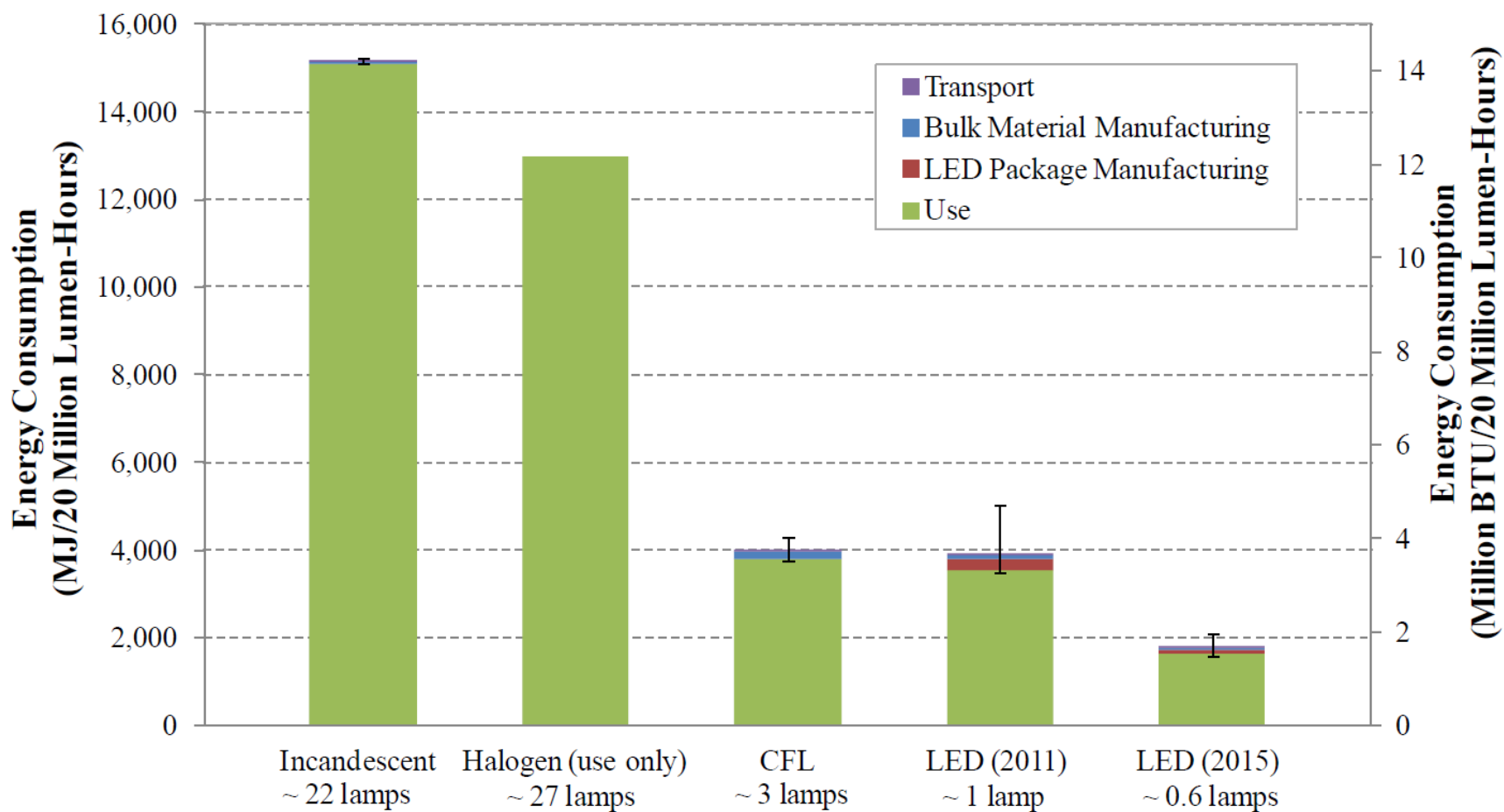


Part 3

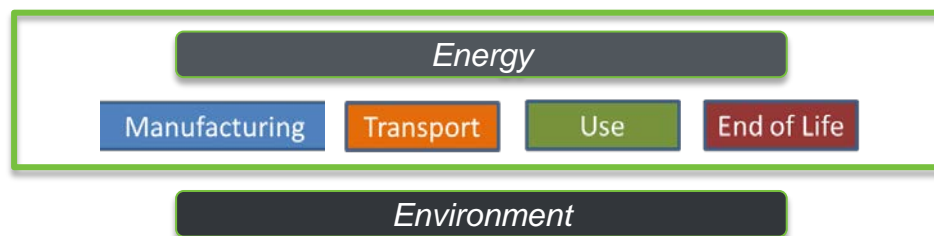
- Completed in February 2012, available at www.ssl.energy.gov/tech_reports.html
- Compared a currently-available LED life-cycle energy consumption to an incandescent lamp and CFL technologies based on 10 literature studies.
- Performed a meta-analysis based on a functional unit of 20 million lumen-hours to compare the studies.



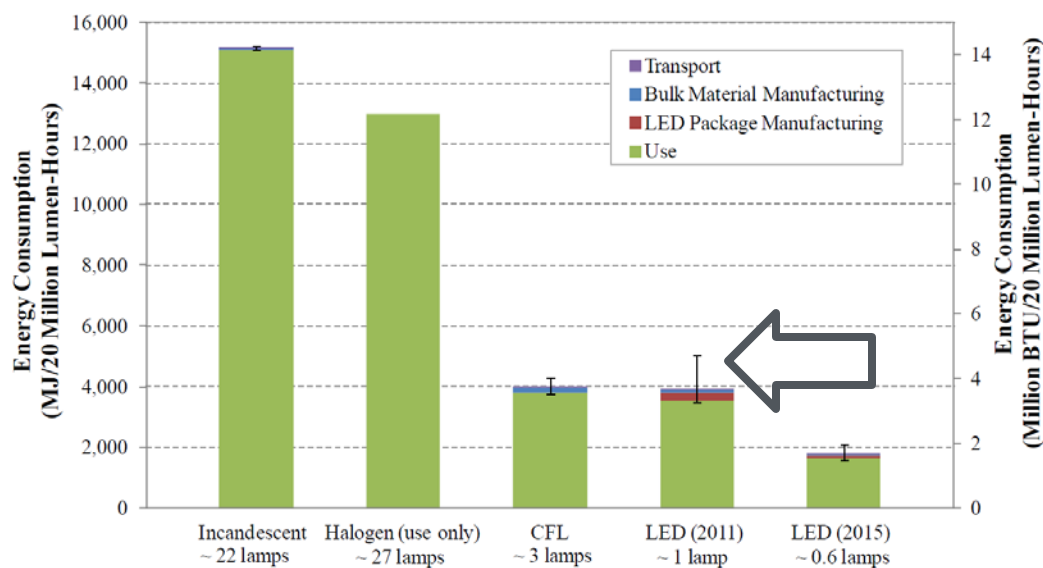
Part 1: Review of the Life-Cycle Energy Consumption of Incandescent, Compact Fluorescent, and LED Lamps



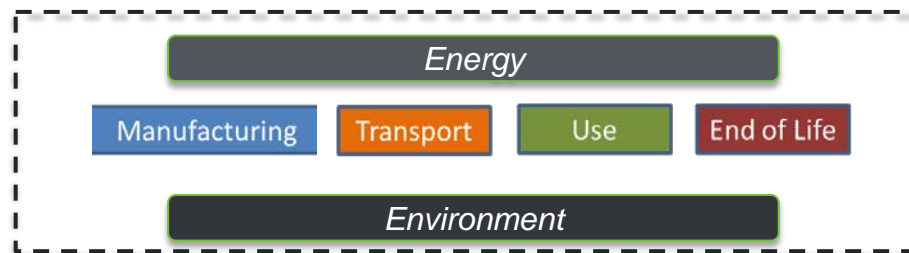
- Concluded that the life cycle energy consumption of LED lamps and CFLs are similar at approximately 3,900 MJ per 20 million lumen-hours. Incandescent lamps consume significantly more energy (approximately 15,100 MJ per 20 million lumen-hours).
- Concluded that the use phase is the most important contributor to the energy consumption, followed by manufacturing of the lamps and finally transportation (less than 1% of energy consumption).



- Identified the high uncertainty in energy consumption associated with the manufacturing process. Estimates in surveyed literature range from 0.1% to 27% of the total life-cycle energy consumption.
- Due to this uncertainty the manufacturing process became a focus for Part 2.

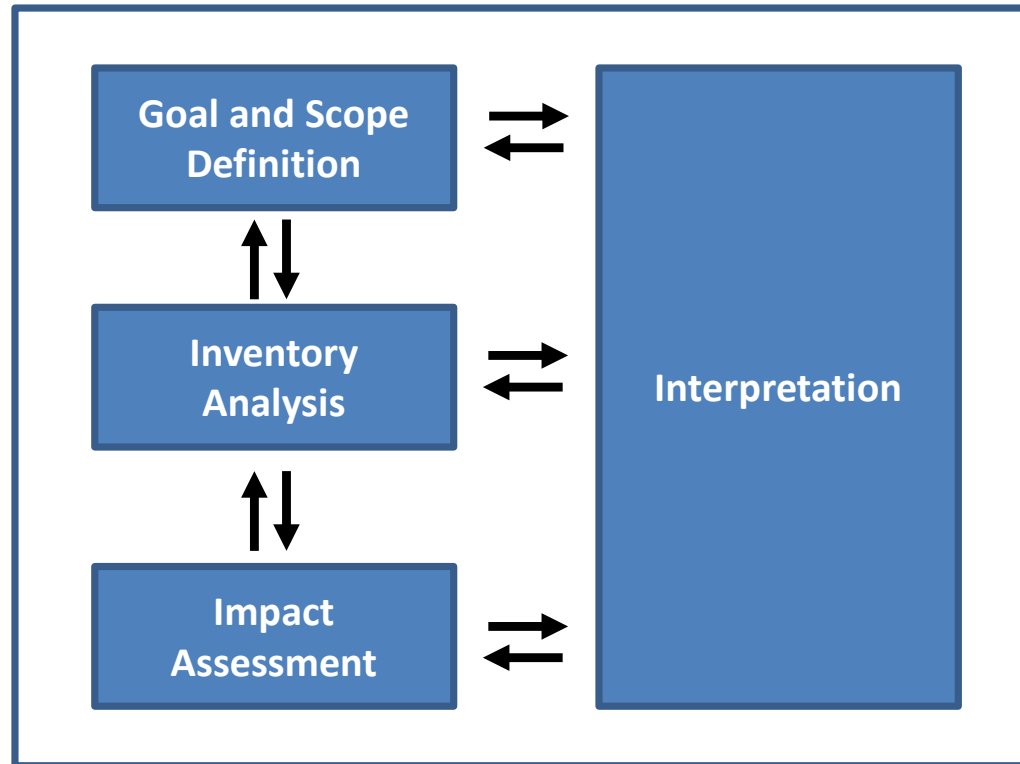


- Completed in June 2012, available at www.ssl.energy.gov/tech_reports.html
- Produced a more detailed and conservative assessment of the LED manufacturing process for lighting applications. No publicly available LCA has provided this before.
- Provided a comparative LCA with other lighting products based on the improved manufacturing analysis with a wider range of environmental impacts.
- Projected comparison of an LED in 2017.



Part 2: LED Manufacturing and Performance Methodology

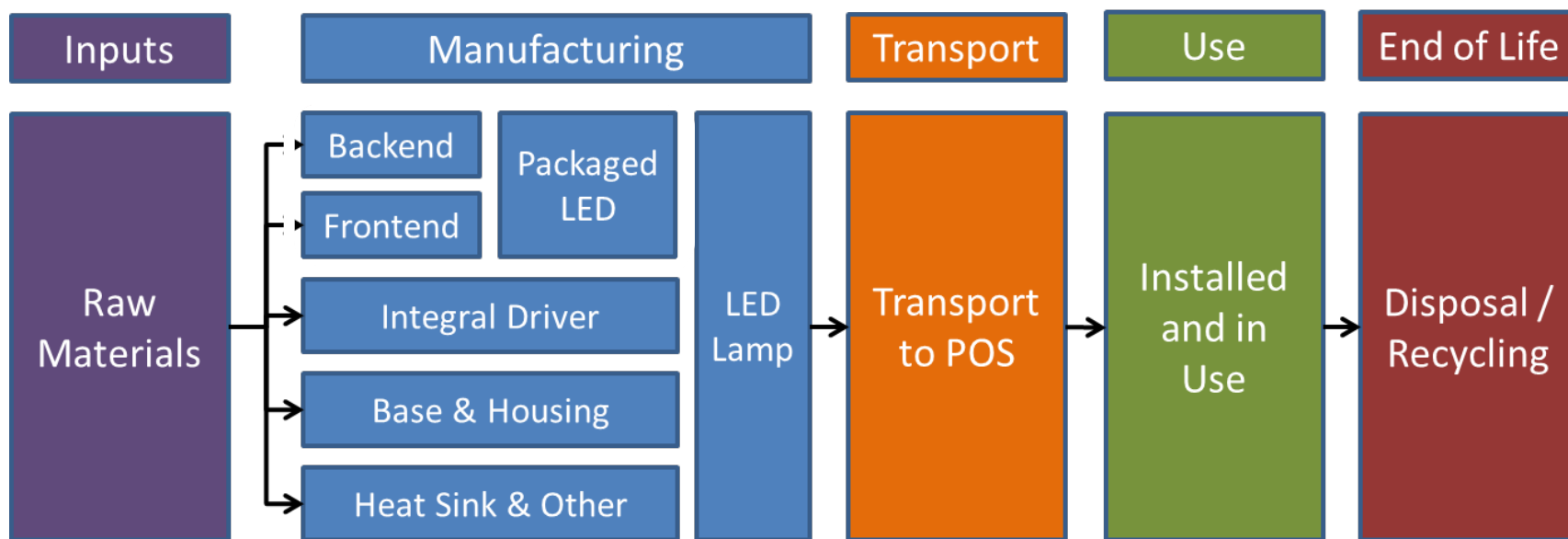
LCA Framework



Source: ISO 14044:2006

Part 2: LED Manufacturing and Performance

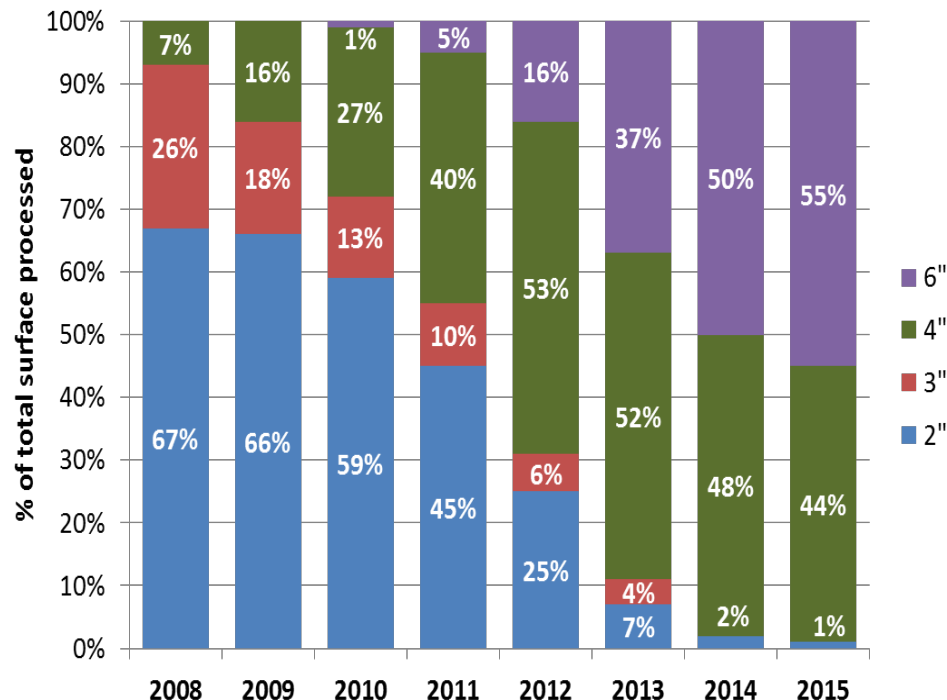
Scope



Part 2: LED Manufacturing and Performance

Representative LED

- ▶ *Three-inch sapphire wafer substrate*
- ▶ *Indium-Gallium Nitride grown on sapphire substrate*
- ▶ *High brightness LED packages (i.e., greater than 0.5 watt / package)*
- ▶ *Deep-blue LEDs (which are pumping a remote phosphor)*
- ▶ *Figure Source: Yole Développement, 2011 as published in Compound Semiconductor, December 2011*



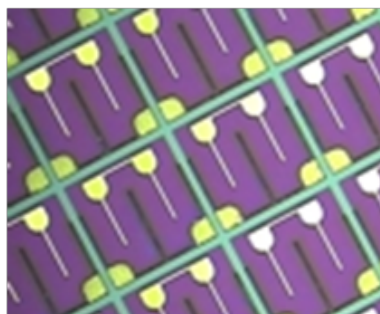
Part 2: LED Manufacturing and Performance

Manufacturing Process



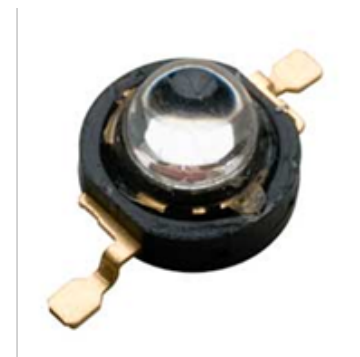
Substrate Production

- Raw materials
- Growing ingots
- Slicing
- Polishing



LED Die Fabrication

- Layering
- Masking / lithography
- Etching
- Die singulation



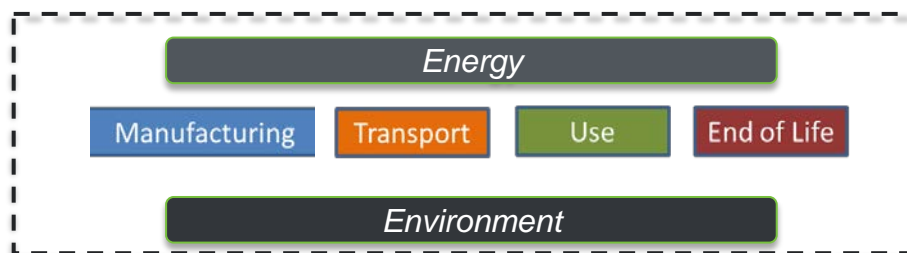
Packaged LED Assembly

- Die testing
- Die attach
- Encapsulation and optics
- Test and binning

Part 2: LED Manufacturing and Performance

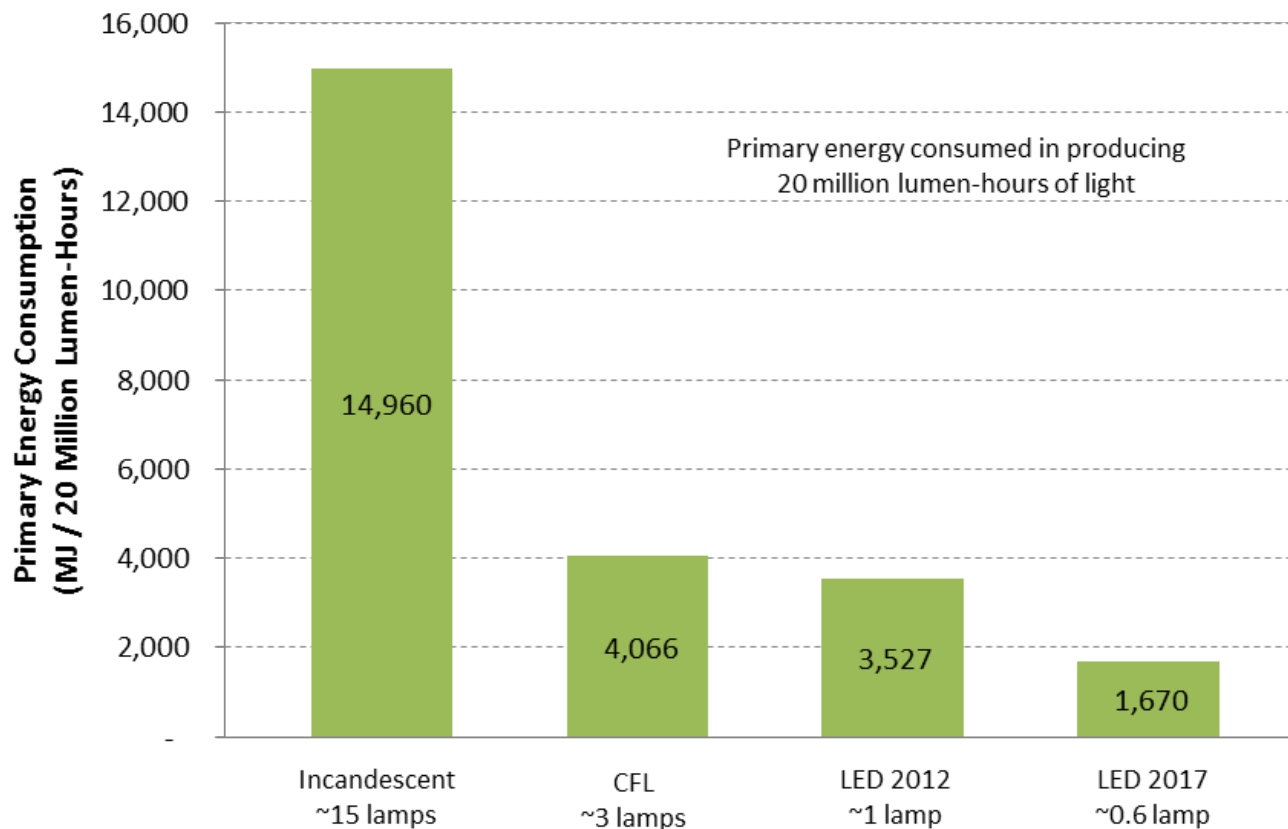
Lamp Characteristics

Characteristics	Incandescent	CFL	LED lamp – 2012	LED lamp – 2017
Power Consumption	60 watts	15 watts	12.5 watts	6.1 watts
Lumen Output	900 lumens	825 lumens	812 lumens	824 lumens
Efficacy	15 lm/W	55 lm/W	65 lm/W	134 lm/W
Lamp Lifetime	1500 hours	8000 hours	25,000 hours	40,000 hours
Total Lifetime Light Output	1.35 Mlm-hr	6.6 Mlm-hr	20.3 Mlm-hr*	33.0 Mlm-hr
Impacts Scalar	15.04	3.08	1.00	0.61



Part 2: LED Manufacturing and Performance

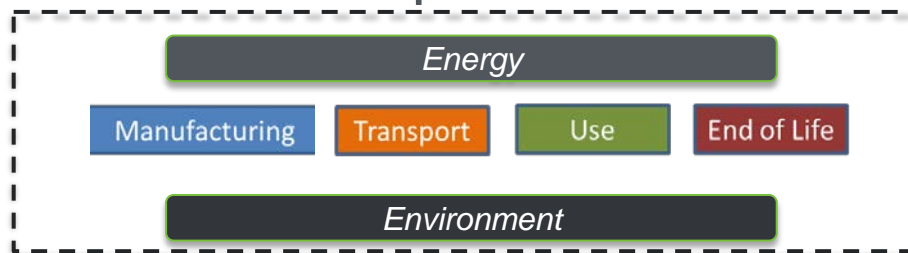
Energy Results



Part 2: LED Manufacturing and Performance

Results

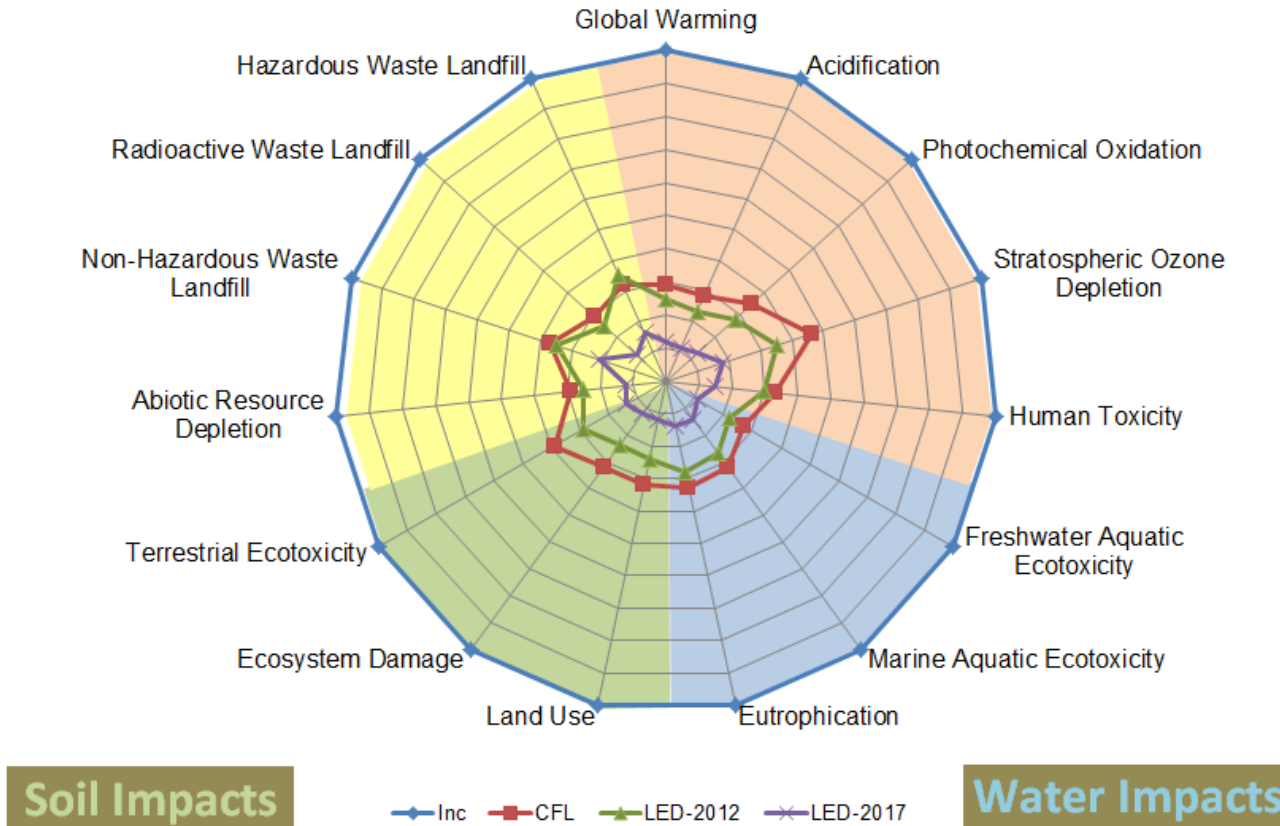
- Confirmed that energy-in-use is the dominant environmental impact, with the 12.5-watt LED lamps and 15-watt CFL performing better than the 60-watt incandescent lamp.
- Concluded that energy-in-use phase of the life-cycle dominates both energy and environmental impacts.
- Concluded the CFL is slightly more harmful than the 2012 integrally ballasted LED lamp against all but one criterion – hazardous waste landfill – where the large aluminum heat sink causes the impacts to be slightly greater for the LED lamp than for the CFL.



Part 2: LED Manufacturing and Performance Results

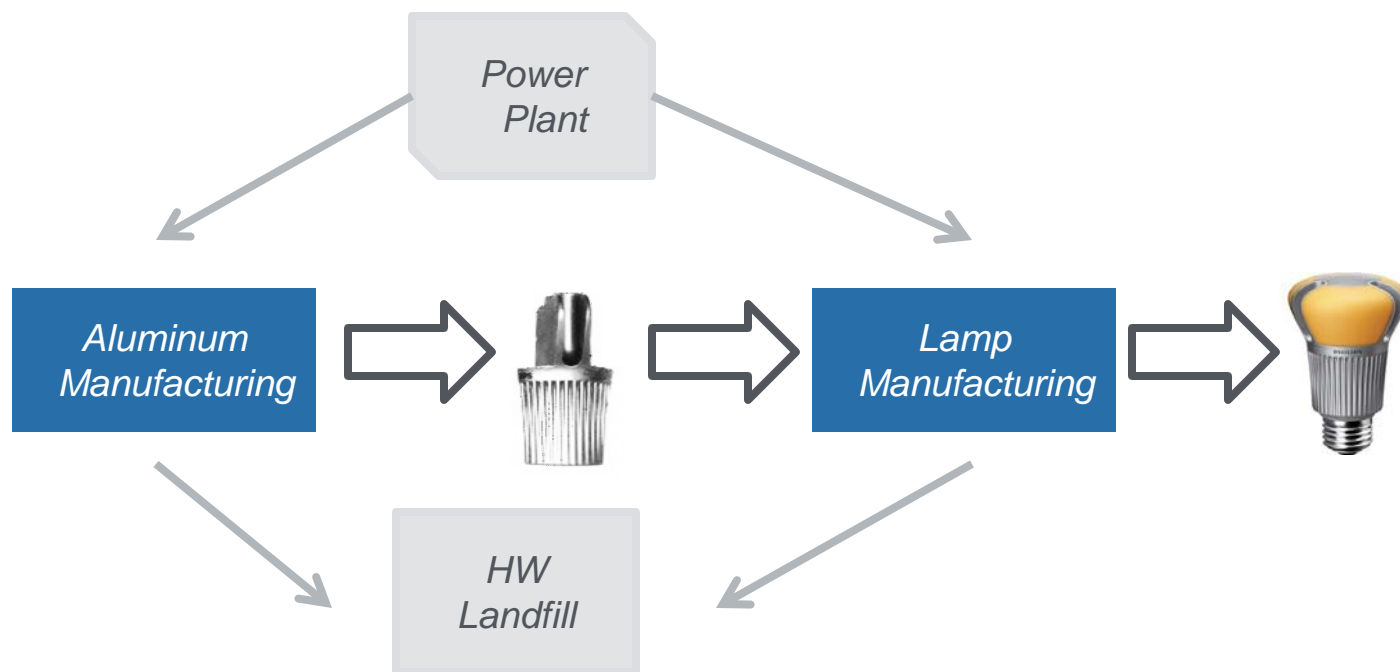
Resource Impacts

Air Impacts



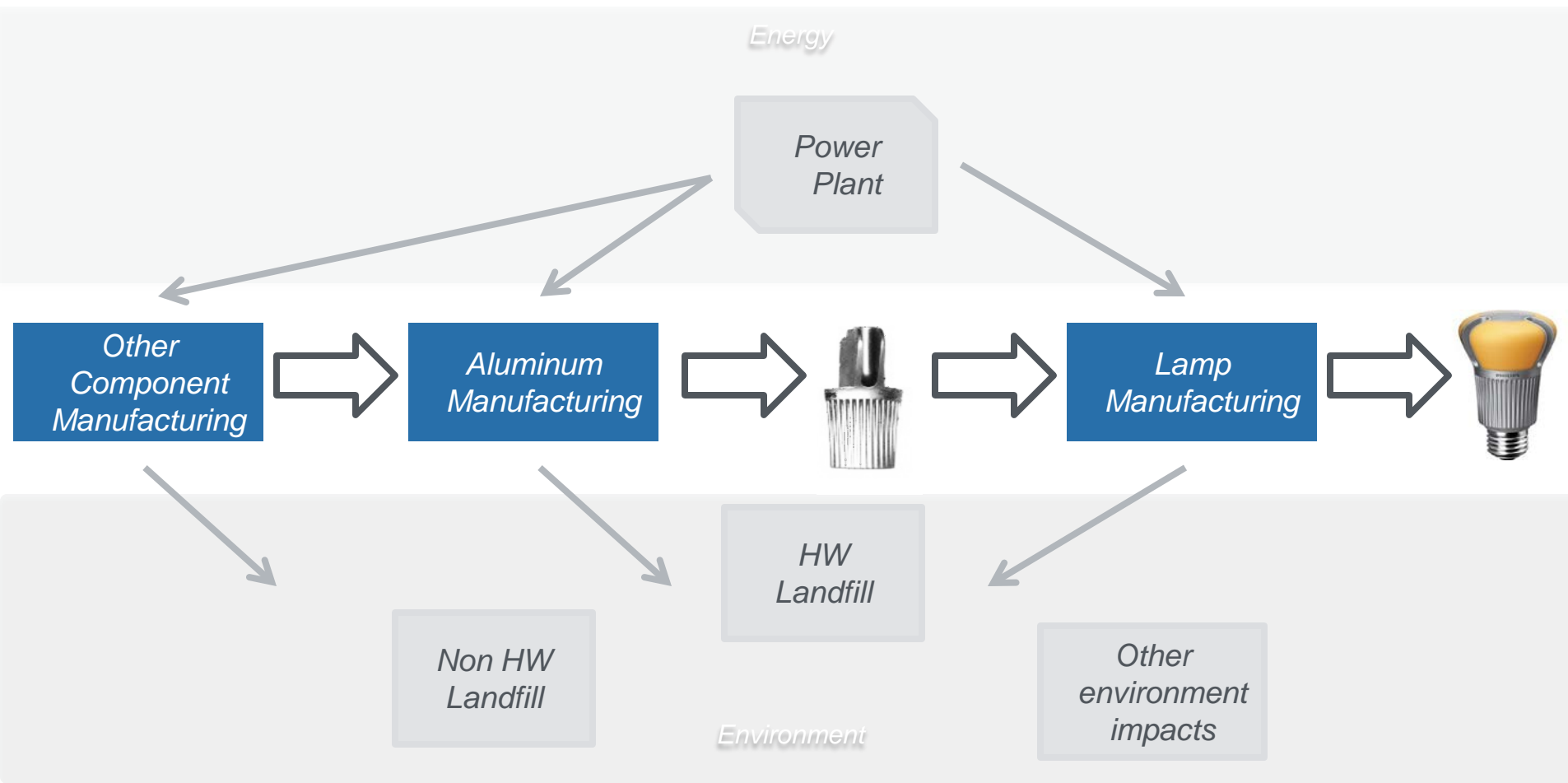
Part 2: LED Manufacturing and Performance

LCA includes upstream



Part 2: LED Manufacturing and Performance

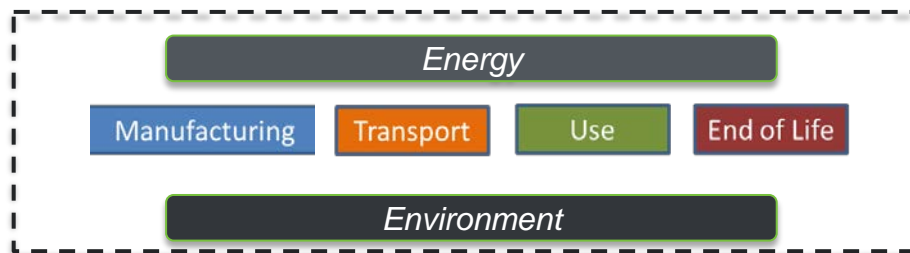
LCA includes upstream



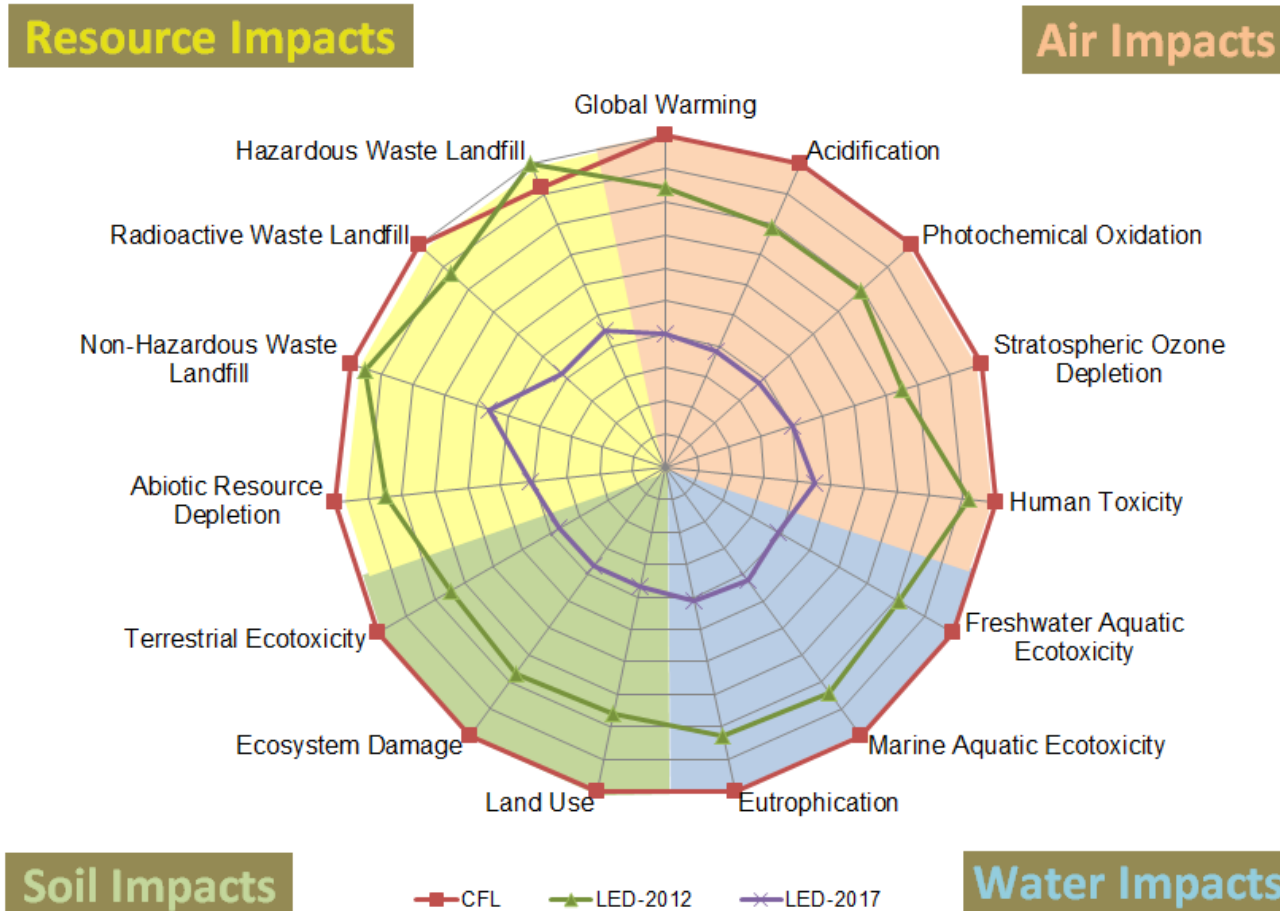
Part 2: LED Manufacturing and Performance

Results

- Determined the best performing light source is the projected LED lamp in 2017, which takes into account several prospective improvements in LED manufacturing, performance, and driver electronics.
- This is of particular interest because LEDs are a rapidly evolving technology and expectations are that it will continue to achieve substantial improvements in its performance in the coming years (DOE, 2012b)



Part 2: LED Manufacturing and Performance Results



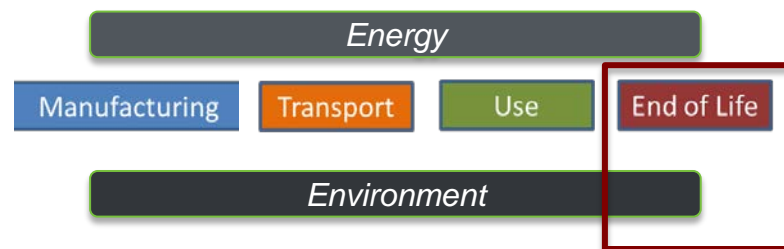
LCA Results

- In the literature reviewed for Part 1 of this study, all but one of the researchers had used the Ecoinvent database entry for the LED.
- This entry is for an indicator LED, and it is based on LED manufacturing technology from 2007
- The indicator lamp was found to have a light output of 4 lumens, while the high-brightness LED was found to have a light output of 100 lumens (Radio-Electronics, 2012; Philips, 2012).
- Overall, the average reduction in impact is 94.5%. Thus, on a lumen output basis, it would appear that high-brightness LEDs manufactured in 2011 are significantly less harmful for the environment than the 5mm indicator LEDs that were produced in 2007.

- Today's LEDs are similar in life cycle energy consumption to CFLs – both using considerably less electricity than incandescent lighting
- LED lamps have a significantly lower environmental impact than incandescent lighting, and a slight edge over CFLs.
- LED manufacturing is evolving rapidly. Predicted improvements in manufacturing and efficacy will make the LED products in 2017 the best option for energy and environment.
- Recycling may improve the life cycle environmental impact of LEDs. End of life will be evaluated in more detail in Part 3 of the study.

Part 3: End of Life

- Determining end of life impact using EPA Method 3050B Acid Digestion of Sediments, Sludges, and Soils to find the Total Threshold Limit Concentration (TTLC) levels.
- When appropriate also applying EPA Method 1311, Toxicity Characteristic Leaching Procedure, and determining the corresponding TCLP values.
- When appropriate also applying apply the California Waste Extraction Test Procedure (WET) described in California Code of Regulations, Title 22, Division 4.5, Chapter 11, Appendix II, and the corresponding STLC values.
- *Translation – we grind up the lighting products and determine concentrations*
- *Translation – we try to figure out what might happen if you put them in a landfill*
- *Translation – when needed we perform an extra test (more rigorous) developed by the state of California.*



- Jason Tuenge, PNNL (jason.tuenge@pnnl.gov)